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Energy spectrum measurement and dose rate estimation of natural neutrons in Tibet region*

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In this work, natural neutron spectra at nine sites in Tibet region were measured using a multi-sphere neutron spectrometer. The altitude-dependence of the spectra total fluence rate and ambient dose equivalent rate were analyzed. From the normalized natural neutron spectra at different altitudes, the spectrum fractions for neutrons of greater than 0.1 MeV do not differ obviously, while those of the thermal neutrons differ greatly from each other. The total fluence rate, effective dose rate and the ambient dose equivalent rate varied with the altitude according to an exponential law.

Keywords: Natural neutron, Spectrum, Effective dose rate, Tibet

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I. INTRODUCTION

The issue of natural radiation effects on human health has always been a focus of the United Nations Scientific Committee on the Effects of Atomic Radiation, and an important part of the issue is about the health effects of natural neutrons [1]. Natural neutrons near ground can be produced from several modes, including the interaction of cosmic ray particles with the atmosphere and surface medias, the capture of cosmic ray particles on the earth and the ground natural radiation [2], and the energy spectrum spans over ten orders of magnitude, from thermal neutrons to high energy neutrons of hundreds of MeV [1, 3]. The measurement of natural neutron energy spectrum is an international hotspot, and laboratories in USA, Japan and other countries have been doing so for half a century [4–11]. Especially, Japan has completed a nationwide survey of the natural neutron radiation level [4]. Although many works on natural neutron dose have been done in China, there is still a need of measuring the nationwide spectrum of natural neutrons [10, 11]. Due to the high altitude and high cosmic ray radiation level in Tibet, the natural radiation dose is higher in Tibet than those of low altitude areas. In this work, measurements with a multi-sphere neutron spectrometer were performed on natural neutron spectrum in areas of different altitudes in Tibet. Altitude variations of the spectrum, total fluence rate, and ambient dose equivalent rate were analyzed. The results provide technical supports and basic data for the radiation survey and radiation hazard assessment on natural neutrons in Tibet.

II. EXPERIMENTAL

A. Instrument

The multi-sphere neutron spectrometer used in this work is shown schematically in Fig. 1. A Φ5.08 cm ^{3}He spherical proportional counter (LND-27036) was used as the thermal neutron detector. The moderator was made of high-density polyethylene (0.94 g/cm^3), being 8 cm, 11 cm, 15 cm and 23 cm in diameter or nothing (bare detector). The moderator balls and the configuration are shown in Fig. 2.

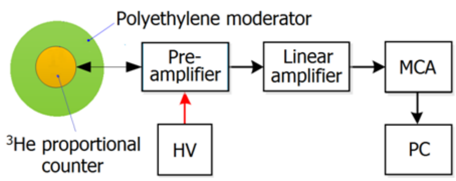

Fig. 1. (Color online) Schematics of the multi-sphere neutron spectrometer system.

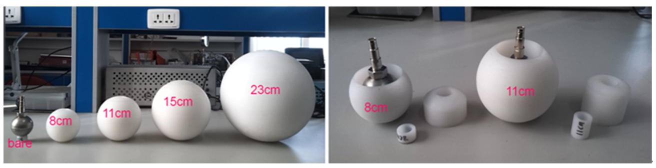

Fig. 2. (Color online) The moderator balls and detector configuration.

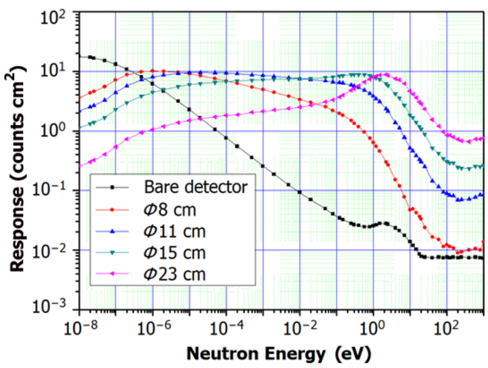

Fig. 3. (Color online) The response functions of the multi-sphere neutron spectrometer.

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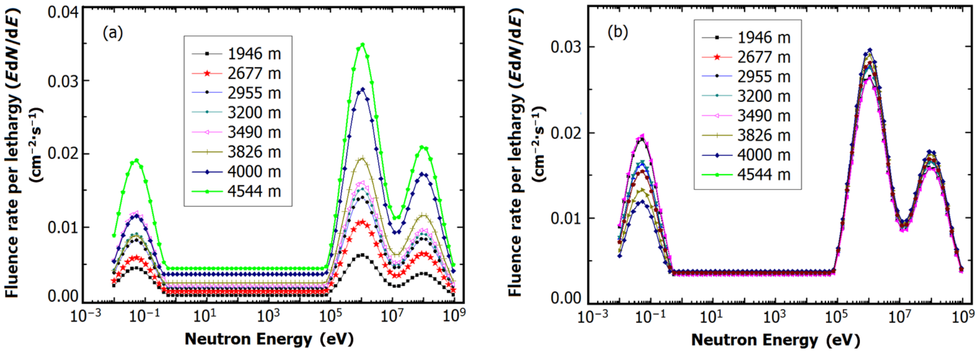

Fig. 4. (Color online) Spectra of natural neutrons at spots of different altitudes in Tibet. (a) as-measured, (b) normalized.

TABLE 1. The altitudes, longitudes and latitudes data

Spot No.	Altitude (m)	Longitude	Latitude	Places
1	1 946	$95°0'52.1''$E	$30°1'45.2''$N	Lulang Town
2	2 677	$95°46'2.4''$E	$29°51'26.8''$N	Bome County
3	2 955	$94°21'39.9''$E	$29°38'1.9''$N	Bayi Town
4	3 200	$93°35'36.5''$E	$29°8'36.4''$N	Gyaca County
5	3 490	$90°53'36.3''$E	$29°17'20.5''$N	Shannan Prefecture
6	3 826	$88°51'30.3''$E	$29°17'21.4''$N	Shigatse Prefecture
7	4 000	$89°5'33.5''$E	$29°40'23.7''$N	Namling County
8	4 544	$90°40'39.2''$E	$30°16'2.6''$N	Nyenchen Tanglsha Mountains pass

The response functions of the multi-sphere neutron spectrometer were calculated with the MCNPX code, using the method in Ref. [12], and the results are shown in Fig. 3. Before the survey, the neutron spectrometer was tested, so as to check its performances. Energy resolutions of the detector coated with different moderator balls were measured at about 7% at 765 keV of reaction ^{3}He(n,p)T, while the detection efficiencies were about 10% as calibrated with ^{252}Cf and ^{241}Am-Be neutron sources. These agreed well with the simulation results.

B. Measurement

Spots of different altitudes in Tibet were chosen and natural neutron spectra were measured at each of the spots using the neutron detector coated with different moderator balls. Conditions of the spectrometer system kept unchanged to measure all the neutron spectra. And each spectrum was recorded in over two hours, with the counts of each moderator ball being greater than 300. The Global Positioning System was used for getting the coordinates and altitudes of the measurement spot.

III. RESULTS AND ANALYSES

A. Neutron energy spectra

The natural neutron spectra obtained using an unfolding program of the least square method are shown in Fig. 4(a), with the altitudes, longitudes and latitudes listed in Table 1. It can be seen that the neutron fluence rates of each energy range increase with the altitude, because the cosmic-ray intensity increase with the altitude. Figure 4(b) shows the neutron spectra normalized to the total fluence rate. The spectrum fractions of neutrons of greater than 0.1 MeV do not differ obviously, while those of the thermal neutrons at different altitudes differ greatly from each other, due possibly to differences in ground media and vegetation at the measurement sites of different altitudes, hence the different moderation and absorption to the natural neutron.

B. Neutron fluence rate and the estimated neutron dose rate

Total fluence rate, effective dose rate and ambient dose equivalent rate were calculated from the measured spectra at each altitude, as given in Table 2. In the calculation, the effective dose per unit fluence for monoenergetic neutrons incident in isotropic geometries to adult male and female reference phantoms calculated by PHITS [13] were used, and the conversion coefficients of ambient dose equivalent rate for monoenergetic neutrons were adopted from the GBZ/T 202-2007 [14].

By fitting the data in Table 2, the altitude variations of neutron fluence rate and neutron dose rate can be obtained, as shown in Fig. 5. It can be seen that the total neutron fluence rate, effective dose and the ambient dose equivalent rate increase exponentially with altitude of the measurement sites, as pointed out in Refs. [1, 15].

TABLE 2. Calculated neutron fluence rate and dose rate at various altitudes in Tibet

Altitude (m)	Atmospheric depth (g/cm^2)	Fluence rate ($cm^{-1}\,s^{-1}$)	Effective dose rate (ISO geometry) (nSv/h)	Ambient dose equivalent Rate(nSv/h)
1 946	811	0.0239	28.2	40.9
2 677	741	0.0388	48.4	70.1
2 955	716	0.0513	63.3	91.6
3 200	695	0.0560	68.6	99.4
3 490	671	0.0620	72.6	105.3
3 826	644	0.0679	87.4	126.4
4 000	630	0.0984	129.2	186.6
4 544	589	0.1254	156.5	226.6

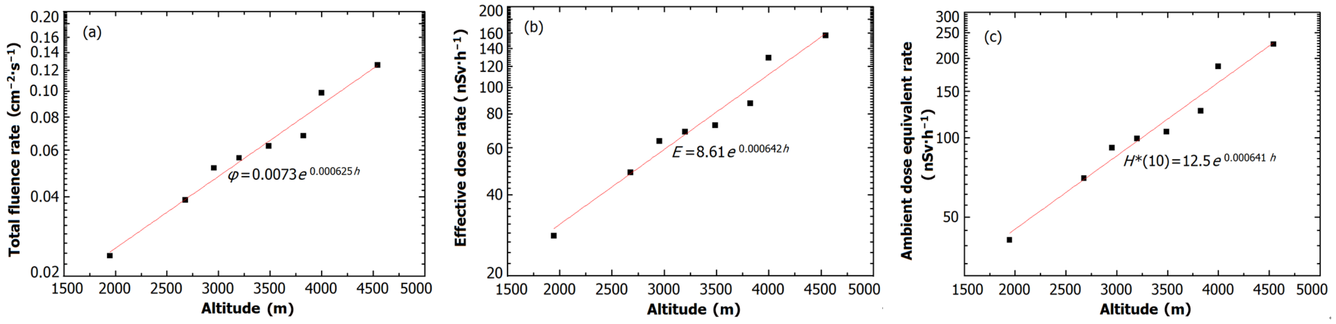

Fig. 5. (Color online) Altitude dependence of the total neutron fluence rate (a), effective dose rate (b) and ambient dose equivalent rate (c).

TABLE 3. Standard deviations (SD) of the α-values

Parameters	α (m^{-1}) $\times 10^{-4}$	SD (m^{-1}) $\times 10^{-4}$
φ	6.25	0.54
E	6.42	0.64
$H*(10)$	6.41	0.62

TABLE 4. The α-values at various geomagnetic latitudes obtained by different groups

Geomagnetic latitude (°)	α-value ($\times 10^{-3}\,m^{-1}$)
18–21	0.625*(This work)
26	0.7 [7]
48	0.78 [1]
49	0.85 [16]
50	1.04 [17]

The variations of the total neutron fluence rate φ, effective dose rate E and ambient dose equivalent rate $H*(10)$ can be fitted by exponential function of $R \cdot e^{\alpha \cdot h}$, where, h is altitude of the measurement sites, R and α are the fitting parameters. The fitted functions were obtained as Eqs. (1), (2) and (3).

$$\varphi = 0.0073e^{0.000625h}, \tag{1}$$

$$E = 8.61e^{0.000642h}, \tag{2}$$

$$H*(10) = 12.5e^{0.000641h}, \tag{3}$$

where φ is in $cm^{-2}\,s^{-1}$, h is in m, and E and $H*(10)$ are in nSv/h.

Standard deviations of the α -values are given in Table 3. It can be seen that the α-values of φ, E and $H*(10)$ are almost the same. This means that the natural neutron spectra changed just a little, so all the α-values calculated from the spectra varied with the altitude nearly in the same way.

Table 4 compared the α-values obtained at various geomagnetic latitudes by different groups. Both the α -value and the latitudes (18°–21°) of the present work are the smallest. This confirms that the α-values increase with the geomagnetic latitude, and that magnitude of the attenuation of natural neutrons is influenced by the geomagnetic intensity [1]. As a result, in order to assess the natural neutron dose in Tibet more accurately, the local α-value should be applied.

IV. CONCLUSION

Natural neutron spectra were measured at nine spots of different altitude: (1946–4544 m) in Tibet region. The effective dose and ambient dose equivalent rate were calculated. The following conclusions can be obtained:

In the normalized natural neutron spectra at different altitudes, the spectrum fractions of neutrons of greater than 0.1 MeV do not differ obviously, but those of the thermal neutrons differ greatly from each other;

The natural neutron fluence rate of each energy range increases with the altitude by $\varphi = 0.0073e^{0.000625h}\,cm^{-2}\,s^{-1}$;

The effective dose rate of natural neutrons varies with the altitude by $E = 8.61e^{0.000642h}$ nSv/h.

[1] United Nations Scientific Committee on the Effects of Atomic Radiation. Sources and effects of ionizing radiation: report to the general assembly with scientific annexes. United Nations, New York, 2000.
[2] Zhang Z X, Wei Z Y, Fang M H, *et al*. Neutron radiation effects of space environment and measuring technique. Equip Environ Eng, 2009, **6**: 5–11. (in Chinese) DOI: 10.3969/j.issn.1672-9242.2009.04.002
[3] Leuthold G, Mares V, Rühm W, *et al*. Long-term measurements of cosmic ray neutrons by means of a Bonner spectrometer at mountain altitudes–First results. Radiat Prot Dosim, 2007, **126**: 506–511. DOI: 10.1093/rpd/ncm102
[4] Nagaoka K, Hiraide I, Sato K, *et al*. Nationwide measurements of cosmic-ray dose rates throughout Japan. Radiat Prot Dosim, 2008, **132**: 365–374. DOI: 10.1093/rpd/ncn316
[5] Hess W N, Patterson H W, Wallace R, *et al*. Cosmic-ray neutron energy spectrum. Phys Rev, 1959, **116**: 445–457. DOI: 10.1103/PhysRev.116.445
[6] Kowatari M, Ohta Y J, Satoh S J, *et al*. Evaluation of geomagnetic latitude dependence of the cosmic-ray induced environmental neutrons in Japan. J Nucl Sci Technol, 2007, **44**: 114–120. DOI: 10.1080/18811248.2007.9711264
[7] Kowatari M, Nagaoka K, Satoh S J, *et al*. Evaluation of the altitude variation of the cosmic-ray induced environmental neutrons in the Mt. Fuji area. J Nucl Sci Technol, 2005, **42**: 495–502. DOI: 10.1080/18811248.2004.9726416
[8] Takada M, Yajima K, Yasuda H, *et al*. Measurement of atmospheric neutron and photon energy spectra at aviation altitudes using a phoswich-type neutron detector. J Nucl Sci Technol, 2010, **47**: 932–944. DOI: 10.1080/18811248.2010.9720972
[9] Alevra A V, Klein H, Knauf K, *et al*. Neutron spectrometry and dosimetry in the environment and at workplace. IRPA Regional Symposium, 1997, **3**: 214–218.
[10] Jiang S H, Yeh J J, Lin R Y, *et al*. A study on natural background neutron dose. IEEE T Nucl Sci, 1994, **41**: 993–998. DOI: 10.1109/23.322846
[11] Weng P S, Chu T C and Chen C F. Natural radiation background in metropolitan Taipei. J Radiat Res, 1991, **32**: 165–174. DOI: 10.1269/jrr.32.165
[12] Wei X Y and Yuan Y G. Simulated response functions of a ^{3}He multi-sphere neutron spectrometer. Nucl Tech, 2010, **33**: 532–537. (in Chinese)
[13] Sato T, Endo A, Zankl M, *et al*. Fluence-to-dose conversion coefficients for neutrons and protons calculated using the PHITS code and ICRP/ICRU adult reference computational phantoms. Phys Med Biol, 2009, **54**: 1997–2014. DOI: 10.1088/0031-9155/54/7/009
[14] Industry Standards of China. GBZ/T 202–2007 Dose conversion coefficients for use in radiological protection against neutron external radiation. Chinese Minist Health, 2007.
[15] O'brien K, Sandmeier H A, Hansen G E, *et al*. Cosmic ray-induced neutron background sources and fluxes for geometries of air over water, ground, iron, and aluminium. J Geophys Res, 1978, **83**: 114–120. DOI: 10.1029/JA083iA01p00114
[16] Florek M, Masarik J, Szarka I, *et al*. Natural neutron fluence rate and the equivalent dose in localities with different elevation and latitude. Radiat Prot Dosim, 1996, **67**: 187–192. DOI: 10.1093/oxfordjournals.rpd.a031815
[17] Bouville A, Lowder W M and Bethesda M D. Human population exposure to cosmic radiation. Radiat Prot Dosim, 1988, **24**: 293–299.